An Overview of Massive MIMO Research at the University of Bristol

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***Abstract*—Massive Multiple-Input, Multiple-Output (MIMO) has rapidly gained popularity as a technology crucial to the capacity advances required for 5G wireless systems. Since its theoretical conception six years ago, research activity has grown exponentially, and there is now a developing industrial interest to commercialise the technology. For this to happen effectively, we believe it is crucial that further pragmatic research is conducted with a view to establish how reality differs from theoretical ideals. This paper presents an overview of the massive MIMO research activities occurring within the Communication Systems & Networks Group at the University of Bristol centred around our 128-antenna real-time testbed, which has been developed through the Bristol Is Open (BIO) programmable city initiative in collaboration with National Instruments (NI) and Lund University. Through recent preliminary trials, we achieved a world first spectral efficiency of 79.4 bits/s/Hz, and subsequently demonstrated a possibility to push this up to 145.6 bits/s/Hz. We provide a summary of this work here along with some of our ongoing research directions such as large-scale array wave-front analysis, optimised power control and localisation techniques.**

***Index Terms*—Massive MIMO, Testbed, Field Trial, Indoor, 5G**

I. Introduction

MIMO has become a mature communications technology in recent years, finding itself incorporated today within both Wi-Fi and fourth generation (4G) cellular standards. Current systems typically deploy between 2 to 4 antennas at the Access Point (AP) or Base Station (BS), and they can be used to either enhance the achievable throughput for a single device or allow 2 to 4 devices to be served simultaneously in the same frequency resource. Massive MIMO takes the latter Multi-user (MU) MIMO concept one step further by deploying hundreds of antennas at the BS, each with their own individual Radio Frequency (RF) chain. The result is greatly enhanced spatial multiplexing performance allowing many tens of User Equipments (UEs) to be served with greater reliability than in standard MU MIMO. It is well-recognised as one of the key enabling technologies for 5G that could provide superior spectral and energy efficiencies. The theoretical benefits of massive MIMO can be found discussed and well documented in [1], [2] and [3].

In this paper, we provide an overview of the massive MIMO research activities occurring with the Communication Systems & Networks Group at the University of Bristol, centred round our 128-antenna real-time testbed. In addition to preliminary results from these first measurement trials, we highlight some of our key areas of interest, including optimised power control algorithms, client localisation and wave front analysis through ray tracing models.

Fig. 1. The BIO Testbed

II. A Pragmatic Focus

The theoretical advantages for moving towards such an extreme case of multi-user MIMO have been widely published over recent years and both academia and industry are now rapidly shifting their focus towards real-world tests. The BIO massive MIMO research platform, previously introduced in [4], has been developed within the Communication Systems & Networks (CSN) Research Group at the University of Bristol in close collaboration with both National Instruments and Lund University, and it has begun to enable a range of pragmatic massive MIMO research and world first results [5] [6]. This section will provide a light overview of our 128-antenna testbed and the two first indoor measurement trials conducted at the University of Bristol.

A. System Overview

The BIO BS prototype consists of 64 NI Universal Software Radio Peripheral (USRP) Reconfigurable Input/Output (RIO) [7] Software-Defined Radios (SDRs) providing 128 RF chains,

TABLE I
SYSTEM PARAMETERS

Parameter	Value
# of BS Antennas	128
# of UEs	12
Bandwidth	20 MHz
Sampling Frequency	30.72 MS/s
Subcarrier Spacing	15 kHz
# of Subcarriers	2048
# of Occupied Subcarriers	1200
Frame duration	10 ms
Subframe duration	1 ms
Slot duration	0.5 ms
TDD periodicity	1 slot

with a further 6 USRP RIOs acting as 12 single-antenna UEs. It runs with an LTE-like Physical Layer (PHY) and the key system parameters can be seen in Table I.

Using the NI Peripheral Component Interconnect Express (PCIe) eXtensions for Instrumentation (PXIe) platform, all the Remote Radio Heads (RRHs) and MIMO Field-Programmable Gate Array (FPGA) processors in the system are linked together by a dense network of gen 3 PCIe fabric, and all software and FPGA behaviour is programmed via LabVIEW. Further detail about the system architecture and the implementation of our wide data-path Minimum Mean Square Error (MMSE) encoder/decoder can be found in [8] and [9].

B. Initial Trials

1) Trial one: The length of the lower atrium in the University of Bristols Merchant Venturers Building was used for three different line-of-sight (LOS) measurements between the BS and 12 UEs. UEs were grouped both in a straight line parallel to the BS and at a slant, with a distance of 3.3m, 12.5m or 18.1m to the nearest client in each scenario. At the BS side, a 5.44m 128-element linear array of dipoles was used, providing half-wavelength spacing at 3.5 GHz. In addition to capturing channel data for offline analysis, we managed to achieve a real-time uncoded sum-rate of 1.59 Gbps in only 20 MHz of Bandwidth (BW), equating to a record spectral efficiency of 79.4 bits/s/Hz [5].

2) Trial two: For the second trial, the upper level of the Merchant Venturers Building atrium was used with a patch panel antenna array to serve user clients placed 24.8m away on the opposite balcony. The array was setup in a 4x32 configuration with alternate H & V polarisations for all 128 antennas. Following a code modification and the provisioning of additional client radios, we were able to perform decimated channel captures and host-based massive MIMO detection for up to 24 users, allowing us to observe recovered constellations and channel statistics in real-time. As with the first trial, the UEs were in LOS and placed in a straight line with 2.5 λ spacing. However, this environment was not so static, as it was a normal working day and students were present. An overview of the setup can be seen in Fig. 2.

Fig. 2. Second measurement trial with the UEs 24.8m away

In the scenario described, we were able to recover clear 256-QAM Uplink (UL) constellations for 22 users. Using the same frame schedule as in trial one, this would scale the achievable real-time throughput and spectral efficiency to nearly 3 Gbps and 145.6 bits/s/Hz respectively [6]. More can be found out about both trials in [8] and [9].

III. CHANNEL & WAVEFRONT ANALYSIS

This section presents an outline of methods that can be used to both analyse and model the propagation characteristics of the massive MIMO channel. Although many of the characteristics inherent in standard MIMO channels are also present in massive MIMO channels, there are some significant differences, such as the need to consider spherical wavefronts rather than plane wave ones [10] and the presence of slow fading across large arrays [11]. The measurement campaigns that have been conducted at the University of Bristol may also be able to reveal other important characteristics of the channel that have not been widely documented as well as providing clarity with regard to known phenomena. Some of the methods that have been used to analyse the characteristics are discussed here. This is followed by an overview of propagation modelling techniques, in particular the ray-tracing system that can be used to enable a more detailed analysis in tandem with the outdoor measurements followed by a description of how different types of wave front models can be used to approximate the channel.

A. Fading Across the Array

The use of the linear array with the testbed allows for the observation of changes across a physically large array Fig. 3. The testbed periodically captures a snapshot of the full channel frequency response between all 128 BS antennas and the 12 single-antenna users for all 1200 Orthogonal Frequency Division Multiplexing (OFDM) subcarriers, with a resolution of one resource block (12 subcarriers). This resolution results from the use of frequency-orthogonal pilots with each user transmitting on every twelfth 15kHz subcarrier originating at its user ID (1-12). The normalised power received at each base station antenna can then be obtained by considering a signal of unity power transmitted from each of the mobile stations, as shown in Fig. 4. Statistical techniques can then be used to extract relevant information that can be compared with the propagation models.

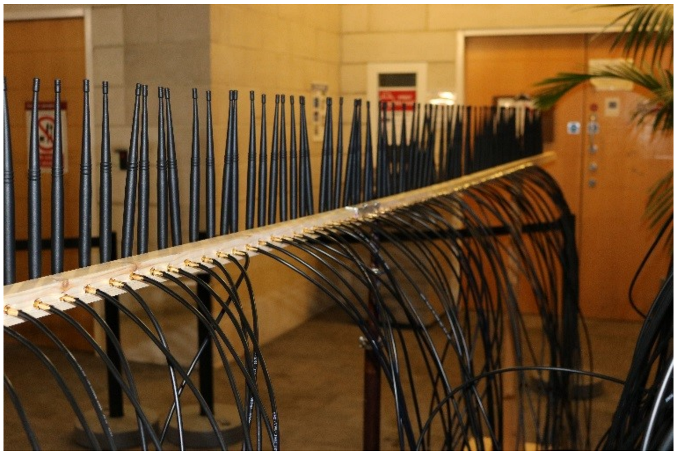

Fig. 3. 5.4m Linear Array of Dipoles used in initial indoor experiment

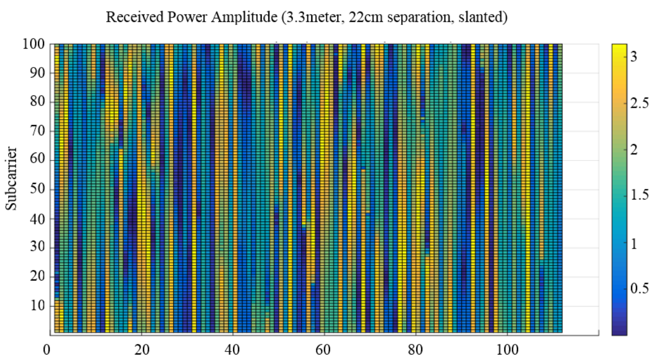

Fig. 4. Normalised power received at each BS antenna for one user

B. Coherence Bandwidth / Delay Spread

It is possible, through the measured data, to be able to obtain not only the coherence BW between two antennas, which is a key parameter for any channel when designing a network, but also to be able to determine how this parameter changes from the perspective of a mobile antenna as it looks across the array from one side to the other. This is possible because, even though the raw data does not include the sampled impulse for each of the resource blocks (with 15kHz separation) it is possible to recover all the relevant sample points by using standard techniques for digital-to-analogue conversion, but in the frequency domain. The time-domain impulse response (which is the power-delay profile) can then be recovered using the Inverse Fast Fourier Transform (FFT) (IFFT), since it is related directly to the frequency domain impulse response.

C. Ray Tracing

The ray-tracing system developed by the University of Bristol allows for the obtaining of a channel impulse response for any transmitter and receiver location by making use of reflection, transmission and refraction [12]. The rays are also calculated in three-dimensions, allowing for the incorporation of antenna patterns. A database of the city of Bristol is available that makes it possible to develop a deterministic model of outdoor measurement campaigns such as the one that was conducted recently near to the Merchant Ventures Building. The ray-tracing system is especially useful for massive MIMO campaigns using a large linear array because it enables experimenters to investigate in detail the changes across the array, and in particular how effects such as slow fading (resulting, for example, from part of the array being shadowed by a building whilst the other part has a LOS link with the mobile user) affect the channel as a whole.

D. Spherical & Planar Models

It is possible, by extending [13], to model the channel matrix as

$$\mathbf{H} = \mathbf{a}_r \mathbf{a}_t^T \tag{1}$$

Where $\mathbf{a}_r$ and $\mathbf{a}_t$ are the spatial signatures for the receiver and transmitter respectively, obtained by making a plane wave assumption across the entire transmit and receive arrays while conveniently not considering each individual antenna element.

Experimental research has shown that a standard planar wave model like this is often inadequate for large linear arrays because of its inability to correctly model the line-of-sight component [14]. This necessitates the use of a spherical wave model that requires a computation of the wave front between each of the antennas such as

$$\mathbf{H}_{m,n} = e^{j\frac{2\pi}{\lambda}\mathbf{r}_{m,n}} \tag{2}$$

where $\mathbf{r}_{m,n}$ is the distance between each transmit and receive antenna, denoted by the subscripts m and n. This inevitably leads to an increase in computational complexity. It is possible to use the measured data both to verify the validity of spherical models but also to be able to determine scenarios where less computational costly approaches could be used instead.

IV. Power Control

Massive MIMO with optimal power control can uniformly improve terminal Signal to Interference plus Noise Ratio (SINR) and improve the performance for users at the cell edge. Like CDMA systems, it is also crucial for mitigating the near-far problem and ensuring balanced performance. In massive MIMO, the channel hardening phenomenon that results from using a large number of antennas at the BS opens up new possibilities for efficient implementation of such algorithms [1]. The channel hardening in massive MIMO was discussed and pictorially illustrated in [15].

Before we designed a power control algorithm for massive MIMO, two experiments took place to investigate the practicality of relying on the channel hardening in our design. Real time channel measurements were captured by the massive MIMO testbed. Twelve single antenna clients were supported simultaneously in both experiments. On the first experiment, the channel was measured by the massive MIMO testbed with only 32 active BS antennas. The distance between the BS and the clients was 20.81 m. Fig. 5 left shows the channel gain matrix for a static indoor environment averaged over 100 captures using 32 BS antennas. On the second experiment,

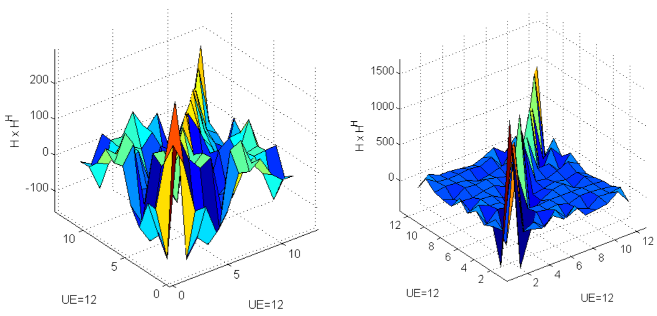

Fig. 5. $\mathbf{HH}^H$ Channel Gram Matrix (not normalised). Left: 32 antennas at the BS. Right: 112 antennas at the BS. 12 single-antenna UEs in each case.

the number of active antennas at the BS was increased to 112, and the distance between the BS and the clients was reduced to 11.6 m. This time, the measurement environment was not static since three people walked randomly between the BS and the clients during the channel measurements, and data was averaged over 400 captures. Fig. 5 right illustrates the greatly improved channel robustness and the channel hardening phenomenon can be clearly seen when 112 active BS antennas was used. By comparing the results from both experiments, the ratio between the eigenvalues and the maximum off-diagonal elements of the channel gain matrix was decreased from 44% into 16%.

Based upon the results obtained from these initial experiments, we designed an uplink power control algorithm for massive MIMO which exploits the channel hardening properties. The aim of our design is to increase the average SINR and the power efficiency whilst simultaneously decreasing the transmission overheads, latency and complexity of the receiver. This design was subsequently implemented and tested on the BIO massive MIMO testbed along with two additional uplink power control algorithms for comparison purposes. The first one is based on a constant Signal to Noise Ratio (SNR) value, whilst the second one is based on a constant SINR value. Following the previous two trials, another indoor experiment took place and the power control was tested in real-time. The environment was changing during channel measurements, although the client devices remained static. The aggregate average SINR was 5.4 decibels (dB) when the power control level adjustment was based on a fixed SNR value. This value was increased by 0.4 when the power level adjustment was based on the SINR. With the power control algorithm we designed, the aggregate average SINR was enhanced by 0.5 dB compared to when a fixed SINR was used.

V. Localisation

Accurate geolocation in urban environments is a challenge. Global Navigation Satellite Systems (GNSS) require LOS communication with at least 3 satellites, which can be difficult in cities due to the urban canyon [16]. Massive MIMO represents an opportunity for mobile radio network based localisation because of the possibility to use inexpensive, low-power and low-precision components, with greatly reduced complexity and cost in terms of antenna requirements and equipment calibration.

Other strong motivations for considering mobile network localisation using massive MIMO are the significant potential benefits this brings to a massive MIMO system itself and possibly other next-generation wireless systems like mmWave. If base stations have information on the location of a mobile device as it moves in the environment, such information can be used in a number of ways that can address some of the challenges of massive MIMO systems. This could prove to be very effective, especially if a BS can build a picture of the environment around it. This gives rise to the following potential benefits:

- New handover strategies. Geolocation information used together with inertial measurements can mean predicting a point where handover will be desirable.
- New resource management strategies. A mobile position can be compared to a posteriori information from heat-map style based tools to implement appropriate adaptive modulation and coding schemes.
- Power Control and reduction in device transmit power. When a mobile device moves from a LOS position to a highly shadowed, Non-line-of-sight (NLOS) position, the change is likely to be abrupt, and closed-loop power control algorithms may struggle leading to power control errors in such a scenario. If power control algorithms can take the location information, together with knowledge of the environment, power control errors could be reduced. Massive MIMO detection is also very robust compared to Single-Input Single-Output (SISO) systems and devices may be allowed to transmit at the minimum levels.
- Reduce pilot contamination in dense deployments. Location-based channel estimation improves the overall system performance. Pilot allocation can be made such that all mobiles with similar Angle of Arrivals (AoAs) are prevented from sharing the same pilot [17].
- Geolocation information can also be used for beamforming especially for mmWave delivery. Localisation can be performed at sub 6 GHz in the mobile network, but the geolocation information can then be used to inform the downlink beamforming for mmWave.

Theory and simulations demonstrate that super resolution schemes like the Multiple Signal Classification (MUSIC) perform better as the number of antenna elements is increased. An array of 100 elements should produce very sharp peaks in the Power-Azimuth Spectrum (PAS), which makes AoA or Angle of Departure (AoD) estimation in massive MIMO very reliable. Furthermore, rectangular arrays would also make elevation AoA/AoD estimation possible. Using the BIO testbed, the performance and limitations of massive MIMO for localisation can be explored. Single BS localisation is possible in scenarios where the mobile device is known to be in LOS, but distribution opens up more opportunities. Due to the modular nature of the testbed, it is distributable into subarrays, and each subsystem can still be synchronised to a common clock. Techniques such as Time-Difference-of-Arrival (TDOA) can then be utilised for mobile clients seeing at least 3 of these distributed arrays.

Most of the potential system benefits identified herein depend on the BSs building a picture of the environment around them. LOS identification for signals between the BS and a mobile client is therefore very critical. LOS and NLOS identification is also a key feature of most localisation algorithms, and for these reasons, identification techniques have been developed and tested using ray tracing simulations based on a real world Laser Illuminated Detection & Ranging (LIDAR) database of the city of Bristol. An assessment of localisation techniques has also been carried out using the ray tracing tools.

VI. Ongoing and Future Work

Future work will include real-time Downlink (DL) performance evaluation, implementation of massive MIMO optimised power control, Over-the-air (OTA) synchronisation optimisation, rooftop deployments and node distribution on the BIO citywide fibre network. The massive MIMO performance will be investigated with different kinds of mobility and suitable power control update rates will be determined for different operational scenarios.

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References

[1] T. L. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590–3600, nov 2010.

[2] J. Hoydis *et al.*, "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?" *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 2, pp. 160–171, feb 2013.

[3] E. G. Larsson *et al.*, "Massive mimo for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186–195, February 2014.

[4] P. Harris *et al.*, "A Distributed Massive MIMO Testbed to Assess Real-World Performance and Feasibility," pp. 1–2, 2015.

[5] "Bristol and Lund set a new world record in 5G wireless spectrum efficiency," 2016. [Online]. Available: http://www.bristol.ac.uk/news/2016/march/massive-mimo.html

[6] "Bristol and Lund once again set new world record in 5G wireless spectrum efficiency," 2016. [Online]. Available: http://www.bristol.ac.uk/news/2016/may/5g-wireless-spectrum-efficiency.html

[7] "USRP-RIO 2943 Datasheet," 2014. [Online]. Available: http://www.ni.com/datasheet/pdf/en/ds-538

[8] P. Harris *et al.*, "Los throughput measurements in real-time with a 128-antenna massive mimo testbed," 2016, accepted for presentation.

[9] ——, "Serving 22 users in real-time with a 128-antenna massive mimo testbed," 2016, accepted for presentation.

[10] Z. Zhou, X. Gao, J. Fang, and Z. Chen, "Spherical wave channel and analysis for large linear array in los conditions," in *2015 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2015, pp. 1–6.

[11] J. Aulin, "Benefits of variation of large scale fading across large antenna arrays," in *2015 9th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2015, pp. 1–5.

[12] G. Athanasiadou, A. Nix, and J. McGeehan, "A ray tracing algorithm for microcellular and indoor propagation modelling," in *Antennas and Propagation, 1995., Ninth International Conference on (Conf. Publ. No. 407)*, vol. 2. IET, 1995, pp. 231–235.

[13] F. Bohagen, P. Orten, and G. E. Oien, "Modeling of line-of-sight 2 ã 2 mimo channels: Spherical versus plane waves," in *2006 IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, 2006, pp. 1–5.

[14] J.-S. Jiang and M. A. Ingram, "Spherical-wave model for short-range mimo," *IEEE Transactions on Communications*, vol. 53, no. 9, pp. 1534–1541, 2005.

[15] T. L. Narasimhan and A. Chockalingam, "Channel hardening-exploiting message passing (chemp) receiver in large-scale mimo systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 847–860, 2014.

[16] "Bristol and Lund set a new world record in 5G wireless spectrum efficiency." [Online]. Available: http://www.gsa.europa.eu/news/results-are-galileo-increases-accuracy-location-based-services

[17] Z. Wang *et al.*, "Location-based channel estimation and pilot assignment for massive MIMO systems," *ICC Workshop on 5G & Beyond Enabling Technologies and Applications*, pp. 1–5, 2015.